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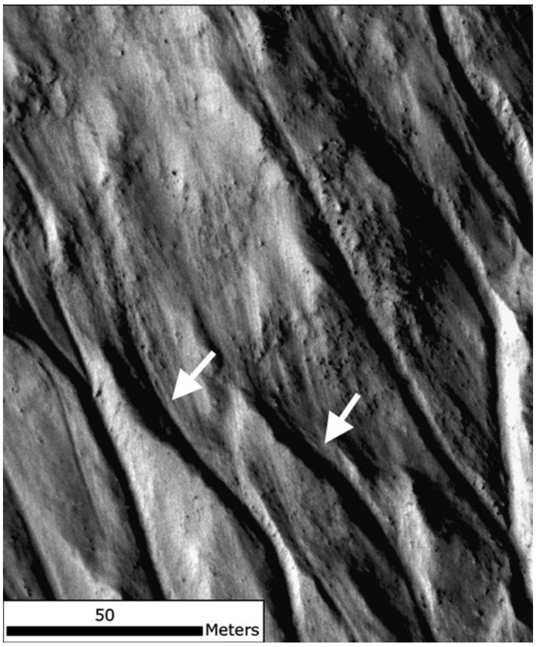

Fig. 6. Gully channels emerging from a section of removed pasted-on terrain (arrows). Boulders can be seen where pasted-on material has been removed, suggesting that the gullies have eroded down to the underlying mesa surface in places. Portion of PSP_007146_2245, with north towards image top, down-slope towards image bottom, and illumination from the lower left.

2005; Oberst et al., 2005; Gwinner et al., 2008) (Fig. 2). Gully channels observed in the study site initiate on steep slopes, averaging 27° ($\sigma = 2°$, range: 24–32°) and transition into fans on more gentle slopes, averaging 21° ($\sigma = 3°$, range: 14–24°) ($N = 300$ for gully channels). Lobate flows are present on still lower inclines, averaging 18° ($\sigma = 4°$, range: 8–25°, $N = 280$). Flows with well-developed lobate snouts are generally present on even lower slopes, averaging 14° ($\sigma = 4°$, range: 6–20°, $N = 20$). These slope angles are broadly consistent with previous gullies measured using HiRISE stereo analysis (Parsons et al., 2008), although it is likely that our slope determinations for sub-grid features (e.g., gully channels) underestimate the slope of steep features (Kreslavsky, 2008b).

4. Surface age

Twelve isolated craters, ranging from 1–10 m in diameter, and a clustered pair of craters reconstructed to pre-fragmentation diameter using the technique of Kreslavsky (2008a), were counted on the surfaces of gully fans and lobes (e.g., Fig. 7). These counts on a ~3 km^2 surface yield a best-fit (Hartmann, 2005) age for the deposits of ~500 ka. The $N(0.01)$ production function determined by Kreslavsky (2007) was applied to the count area and produced an identical age based on one > 10 m impact crater that is clearly present on a gully fan surface, but which has been modified by lobe-related activity. While small numbers of craters and a small count area make precise age dating challenging, these surface age measurements are broadly consistent with youthful ages for typical martian gullies determined from stratigraphic analyses by Riess et al. (2004) and Schon et al. (2009).

5. Discussion

To date, morphological features similar to the lobes identified in this study have not been identified in comprehensive HiRISE image surveys of martian gully terrain, despite several thousand gully observations (McEwen et al., 2007; Dickson and Head, 2008; Levy et al., 2009b, McEwen et al., in press). The proximity of the lobes to martian gullies, and their apparent uniqueness in the martian landscape, suggests that they may provide critical insight into the formation mechanisms and hydrological significance of martian gullies. First, we assess morphological differences and similarities between the lobe deposits observed in this study and classical martian gullies. Next we compare the deposits to the continuum of mass-movement processes that produce similar morphologies on Earth. Through analysis of terrestrial processes, we are able to determine the significance of these unusual deposits by placing them in the spectrum of martian gully-forming mechanisms.

5.1. Similarities and differences with classic martian gullies

The Protonilus Mensae mesa analyzed in this study is broadly typical of martian gullied terrain that has been mapped in several surveys using high-resolution image data (Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007a; Heldmann et al., 2007; Dickson and Head, 2008; Levy et al., 2008). Channel and fan structures present on the mesa illustrate two of the three elements considered diagnostic of martian gullies (alcoves, channels, and fans) (Malin and Edgett, 2000). Identification of two of these three elements is a criterion commonly used for mapping features as gullies in large-scale surveys (Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007a; Dickson and Head, 2008). The channels dissect pasted-on terrain (Christensen, 2003), illustrating a typical relationship between martian gullies and latitude-dependent mantle deposits (Mustard et al., 2001; Christensen, 2003; Head et al., 2003; Milliken et al., 2003; Berman et al., 2005; Dickson et al., 2007a; Dickson and Head, 2008; Levy et al., 2009b). Like many gullies, some of the observed gully channels are sinuous; some smaller channels in the study site show sinuosity on length scales of meters, while some of the larger channels bend on tens of meter scales. Small-wavelength sinuosity may represent gully channel response to fine scale topography, while tens of meter wavelength has been interpreted by Mangold et al. (2008a,b) to be strongly indicative of the presence of a liquid water phase in gully channel eroding flows. The gullies are present on the south (equator-facing) side of the mesa only, a typical orientation for the relatively few martian gullies observed in the northern hemisphere near 45° latitude (Bridges and Lackner, 2006; Heldmann et al., 2007). Like other martian gullies, these gullies initiate on extremely steep slopes, typically approaching 30°, and deposit fans on lower-slope surfaces (Dickson et al., 2007a; Parsons et al., 2008). The fans of the analyzed gullies commonly have irregular toes or termini, as identified in MOC images (Malin and Edgett, 2000), in part owing to the complex stacking of fan depositional and erosional surfaces documented on many martian gully fans (e.g., Schon et al., 2009). Some fans in the study site are composed of multiple depositional fronts, typical of young gullies interpreted to have formed by episodic flow (Schon et al., 2009).

Despite their similarities to other martian gullies, the features present on the Protonilus Mensae mesa exhibit several morphological characteristics that are atypical of gullies forming in classic gully environments (mesa sides, crater rims, etc.). The observed gullies in Protonilus Mensae are unusual in that most lack well-defined alcoves—either incised into the mesa (e.g., Malin and Edgett, 2000) or developing in the pasted-on terrain (e.g., Christensen, 2003; Levy et al., 2009a,b,c). Rather than emanating from alcoves, the observed gully channels appear continuous with fine, narrow channels that are present higher up on the mesa, and which widen as the channel slope steepens—a relationship not previously observed for gullies on Mars (Dickson and Head, 2008). The Protonilus gully channels are unusually closely spaced (over 300 channels dissect the ~5 km scarp). Typical mesa or butte gullies on Mars are either singular features, or occur in groups of <~20 (Heldmann and Mellon, 2004; Dickson et al., 2007a; Dickson and Head, 2008; Head et al., 2008). The channels are unusually straight and parallel